High Average Power Laser Program (HAPL) with notes on earlier IFE studies and current ARPA-E BETHE IFE program

IFE workshop kickoff meeting

16 November 2021

Stephen Obenschain
Laser Plasma Branch
Plasma Physics Division

Organized IFE efforts in the U.S

NRL PPD

Early 1990's point design and cost analysis of IFE reactors

Sombrero 3.4-MJ KrF direct drive
Osiris 5 MJ heavy ions ID

Prometheus-L 4-MJ KrF direct drive
Prometheus-H 7-MJ heavy Ions ID

High Average Power Laser (HAPL) laser direct drive IFE program (1998-2009)

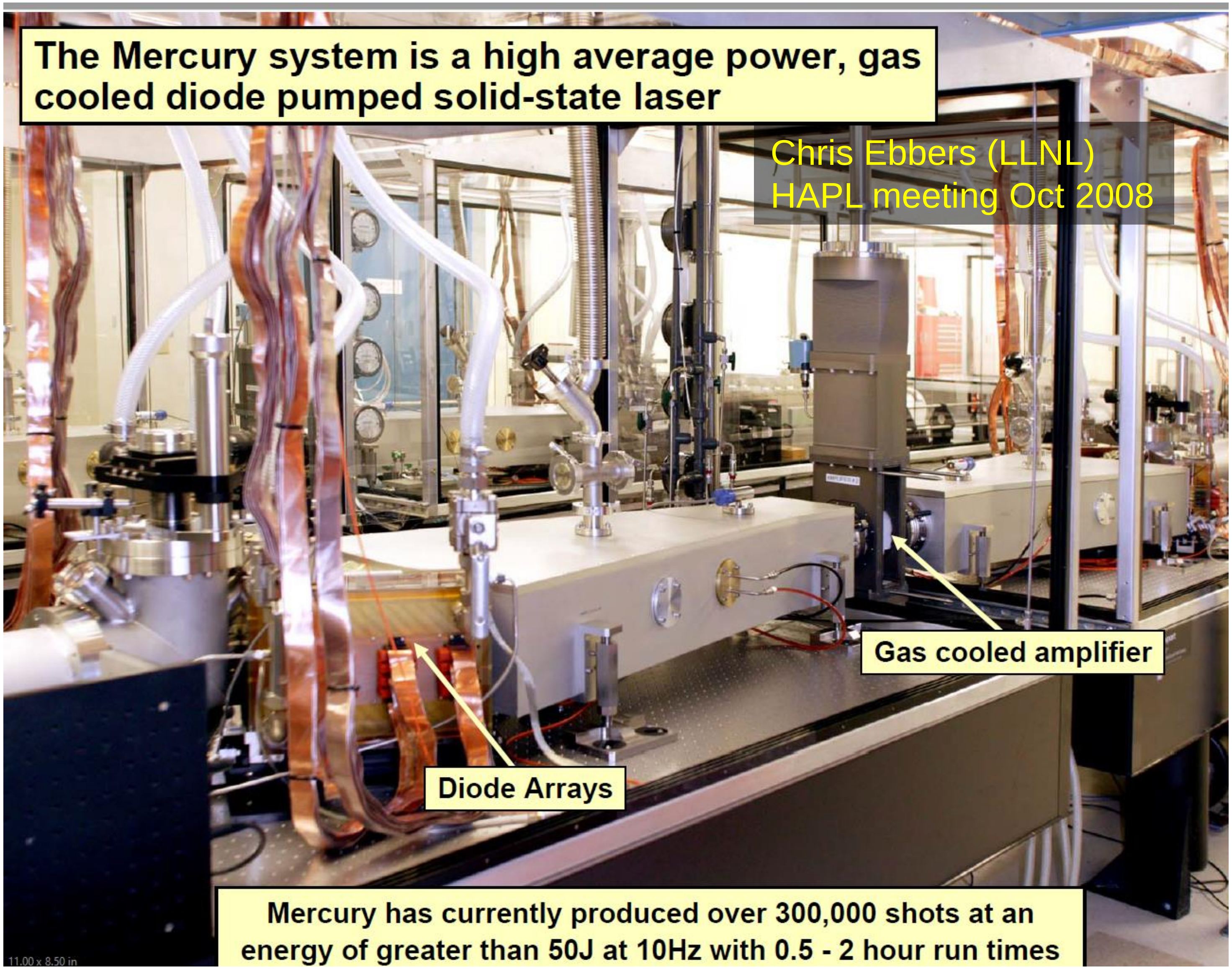
- Krypton fluoride (KrF) and diode pumped solid state (DPSSL) high-rep-rate lasers
- Other essential technologies: e.g. low cost target fab, target injection, final optics
- System approach: look for conflicts such as gas fill of chamber interfering with target injection.

Laser Inertial Fusion Energy (LIFE) Glass DPSSL indirect drive (next presentation)

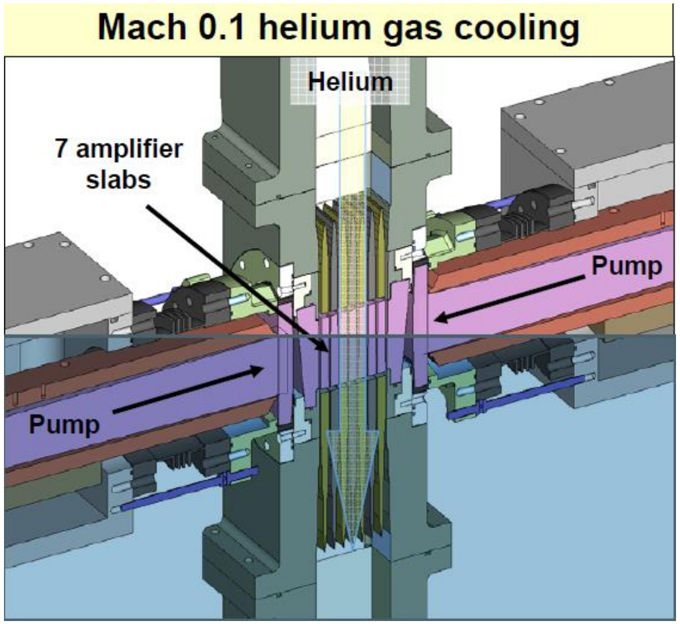
ARPA-E & FES supported BETHE laser IFE program (2020-present)

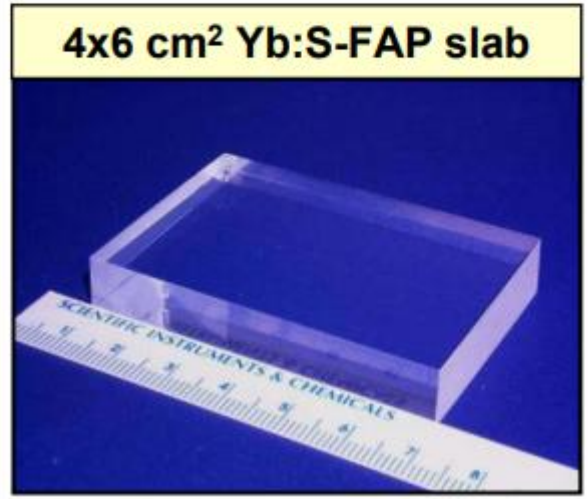
- Reduce size and cost of laser direct drive power plants
- Mitigate laser plasma instability – broad bandwidth and short laser wavelength

Mercury high rep rate DPSSL @ LLNL

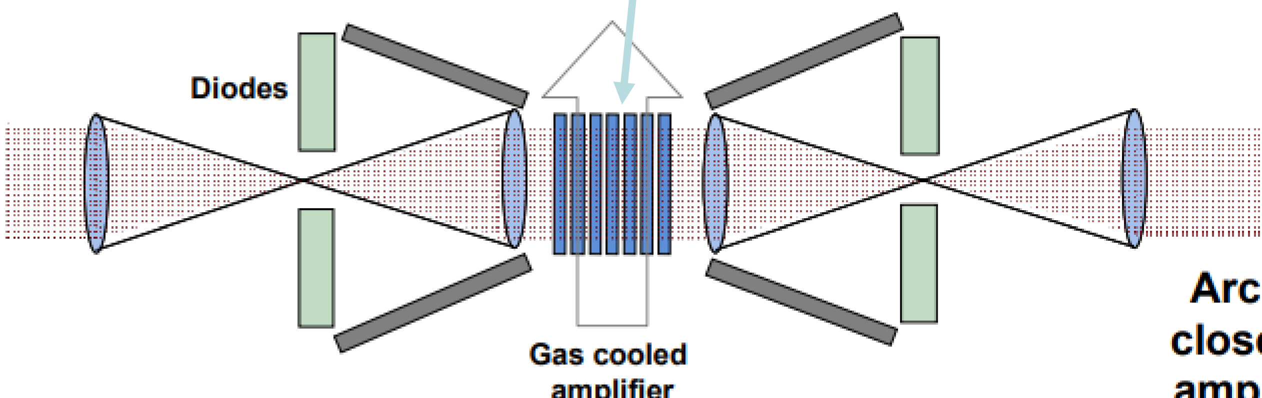


Mercury DPSSL technologies



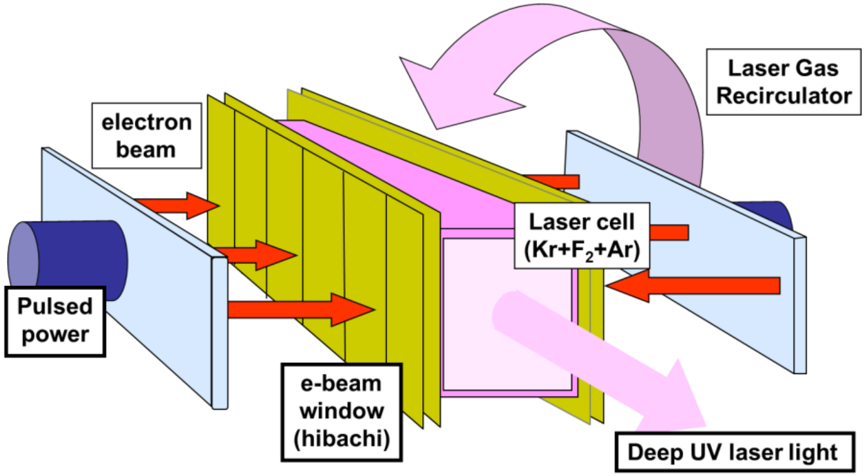


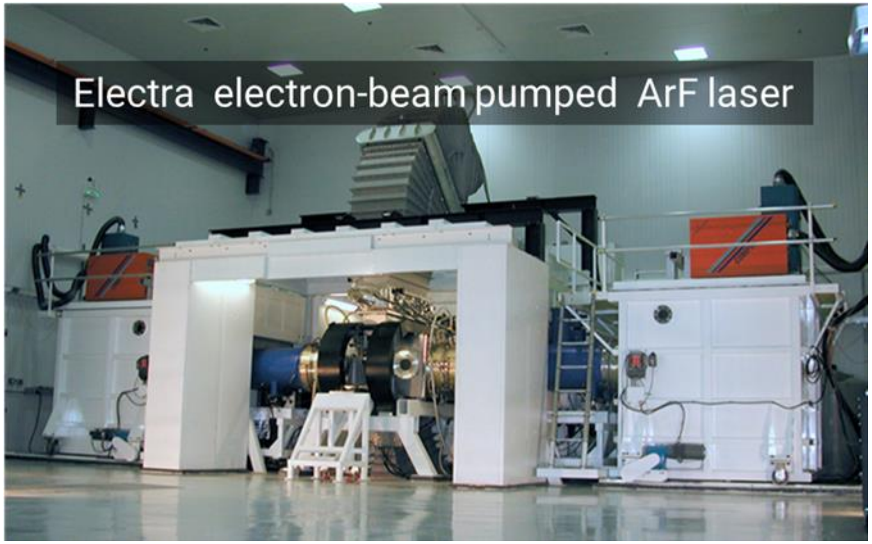
Yb:S-FAP has longer storage time than Nd:glass – 3x fewer laser diodes required



Architecture: closely-spaced amplifier slabs

Electra high rep rate electron beam pumped KrF @ NRL





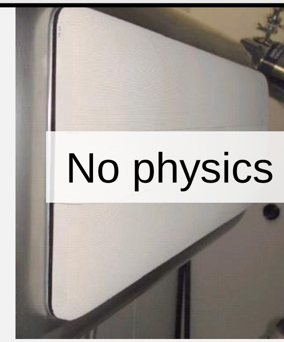
Performance:

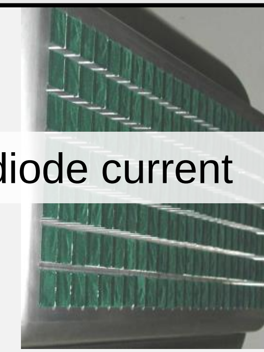
- Up to 750 J with configuration for high E-beam transmission into laser gas
- Up to 5 pulses per second for thousands of shots – duration limited by overheat of spark gas switches
- 100,000 shots continuous @ 2.5 Hz

Electra KrF laser technologies

All solid state switched 200 kV 6 KA pulse power system 10 million shots continuous

Larger amps like NRL Nike 60-cm amp. exhibit a transit time instability, 2 means to suppress instability developed



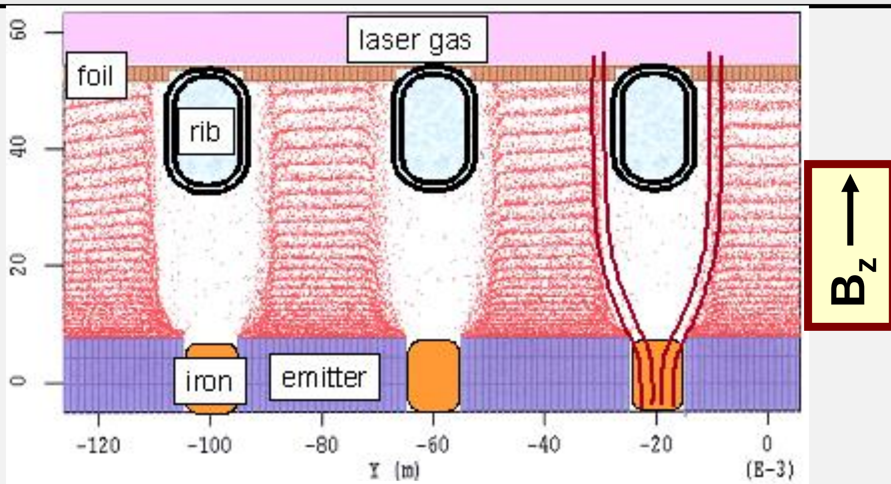


No physics limit on diode current

Ceramic Cathode

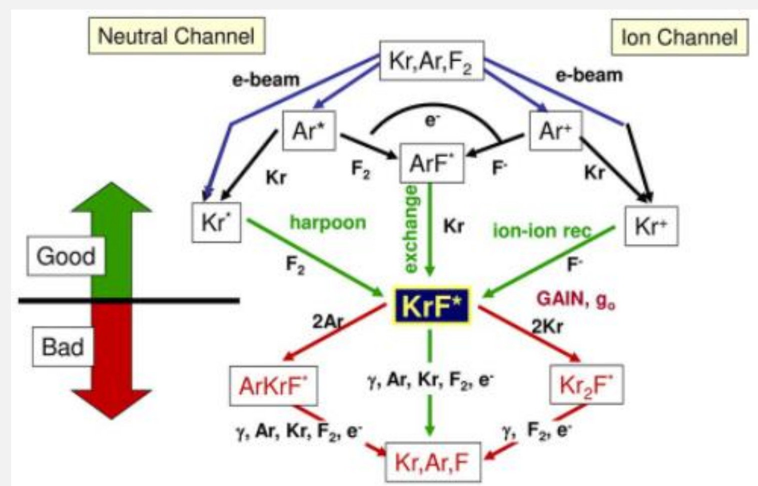
Patterned cathode

Structured cathode so e-beam misses foil ribs

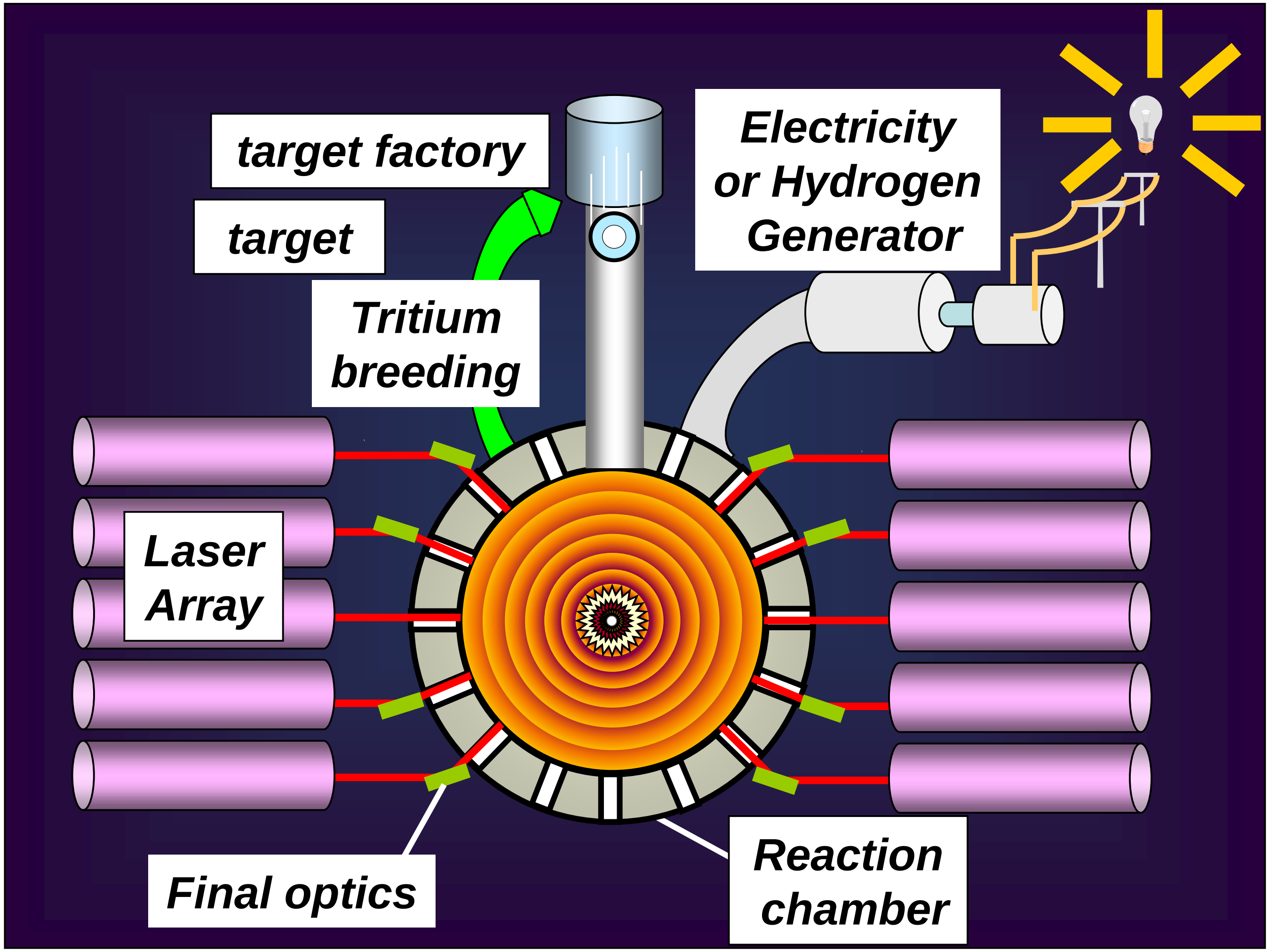


75% e-beam transmission into gas

Orestes Kinetic KrF code



Development of other (than laser) science and technologies needed for direct drive IFE



John Sethian,
Naval Research Laboratory

EPRI Fusion Assessment Workshop
Palo Alto, CA, July 20, 2011

Summary

1. We have carried out an integrated program to develop credible approaches for most all the key components needed for laser IFE
   a. Final Optics
   b. Target Fabrication
   c. Target Injection
   d. Target Engagement
   e. Chamber Technologies
   f. Auxiliary systems (tritium processing, vacuum, maintenance)

2. Many of these were demonstrated in subscale experiments.

3. Studies suggest this approach may be a viable way to produce hydrogen, as well as electricity

4. Path to materials/component testing and development

Other key components needed for IFE addressed by multi-institutional US HAPL Program (1999-2009)

19th HAPL meeting
Oct 22-23, 2008
Madison, WI
54 participants, 10 students

Government Labs
1. NRL
2. LLNL
3. SNL
4. LANL
5. ORNL
6. PPPL
7. SRNL

Universities
1. UCSD
2. Wisconsin
3. Georgia Tech
4. UCLA
5. U Rochester, LLE
6. UC Berkeley
7. UNC
8. Penn State Electro-optics

Industry
1. General Atomics
2. L3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. PLEX Corporation
14. APP
15. Research Scientific Inst
16. Optiswitch Technology
17. ESLI

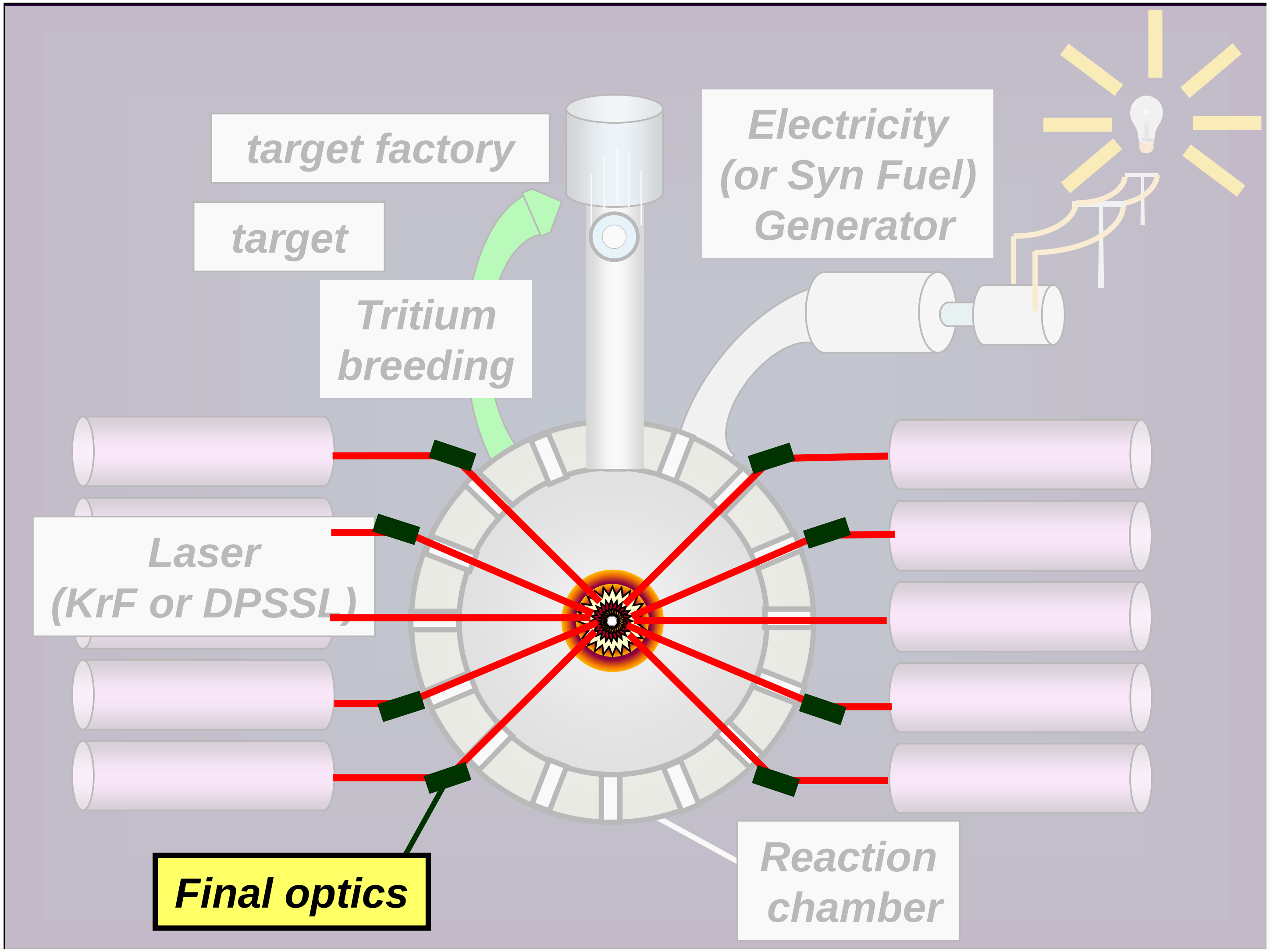
IFE Technology Development

Each component developed separately,
but as part of an integrated system

Presentation Organization:

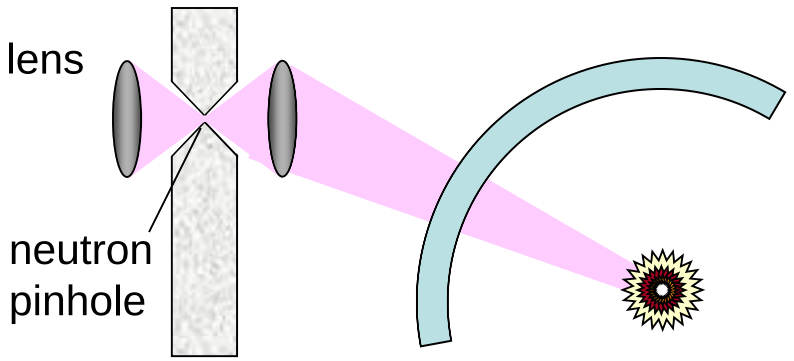
- Options considered
  - Basis for choice
  - Progress

FINAL OPTICS



Final Optic Options evaluated

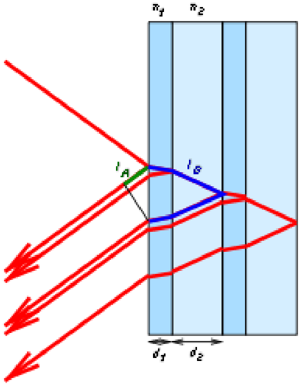
Lens plus pinhole



Good:
- ♦ Neutron damage annealed > 500 °C **(351 nm only)**

Challenge:
- ♦ No KrF material identified
- ♦ Fielding large, heated, thin, optic
- ♦ Pinhole may constrain target optics
- ♦ Long term residual damage?

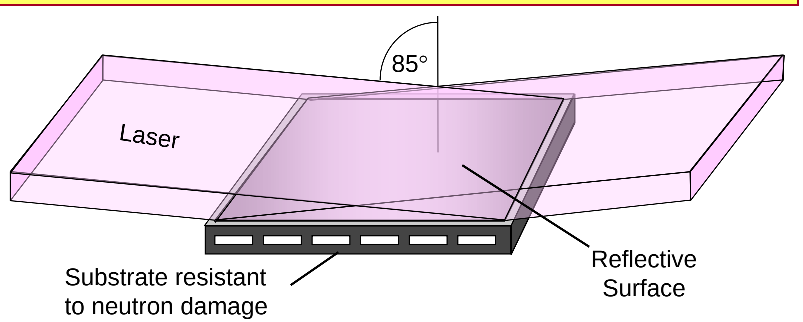
Dielectric Mirror



Good:
- ♦ Very high reflectivity
- ♦ High laser damage threshold

Challenge:
- ♦ Literature shows neutron damage

Grazing Incidence Metal Mirror

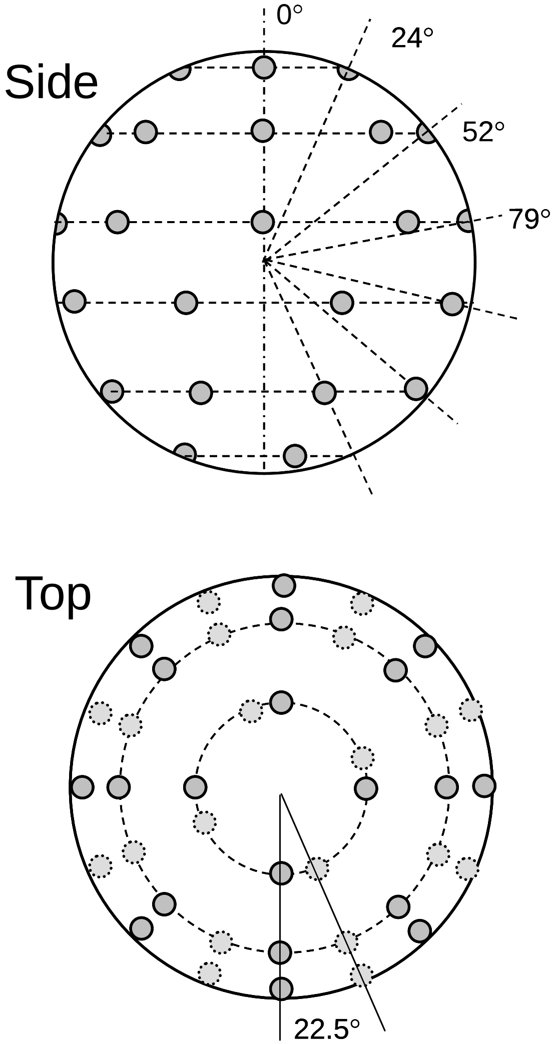


Good:
- ♦ Can make base resistant to neutrons
- ♦ Shown required damage threshold

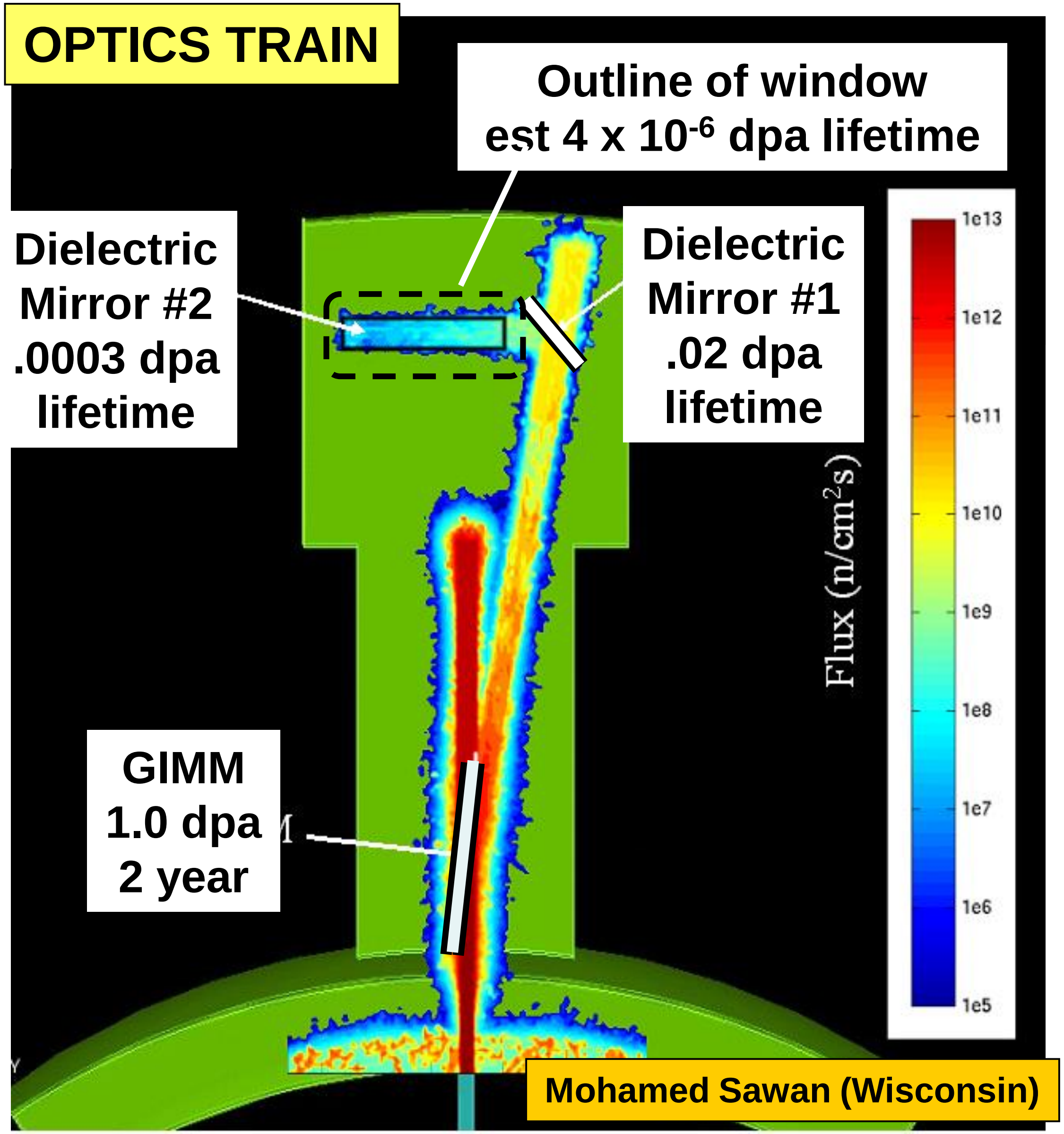
Challenges:
- ♦ Large optic

Chamber Ports and Optical Train

PORT POSITIONS

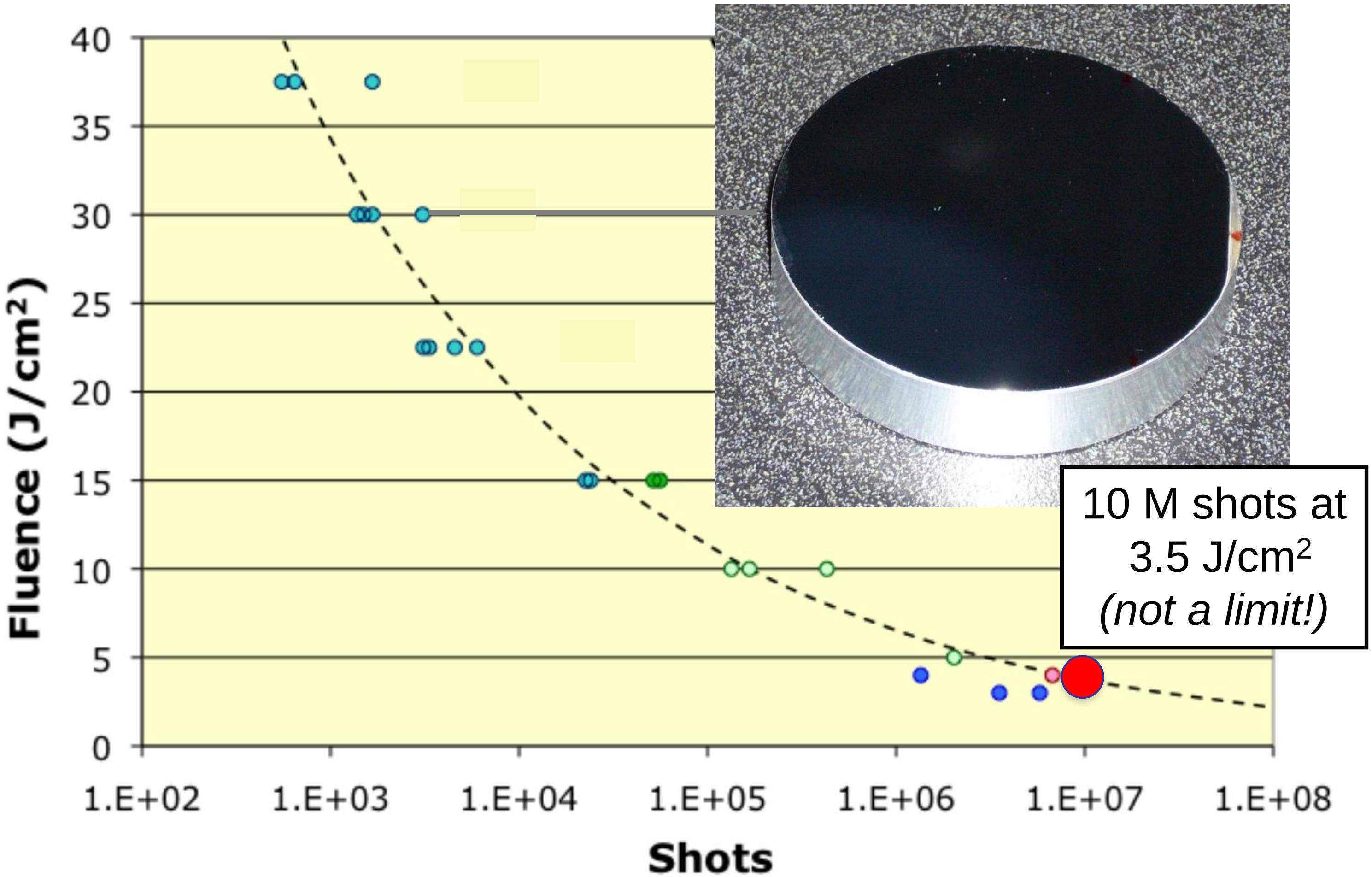


OPTICS TRAIN



Mohamed Sawan (Wisconsin)

GIMM laser damage threshold: > 3.5 J/cm^2 @ 10 M shots



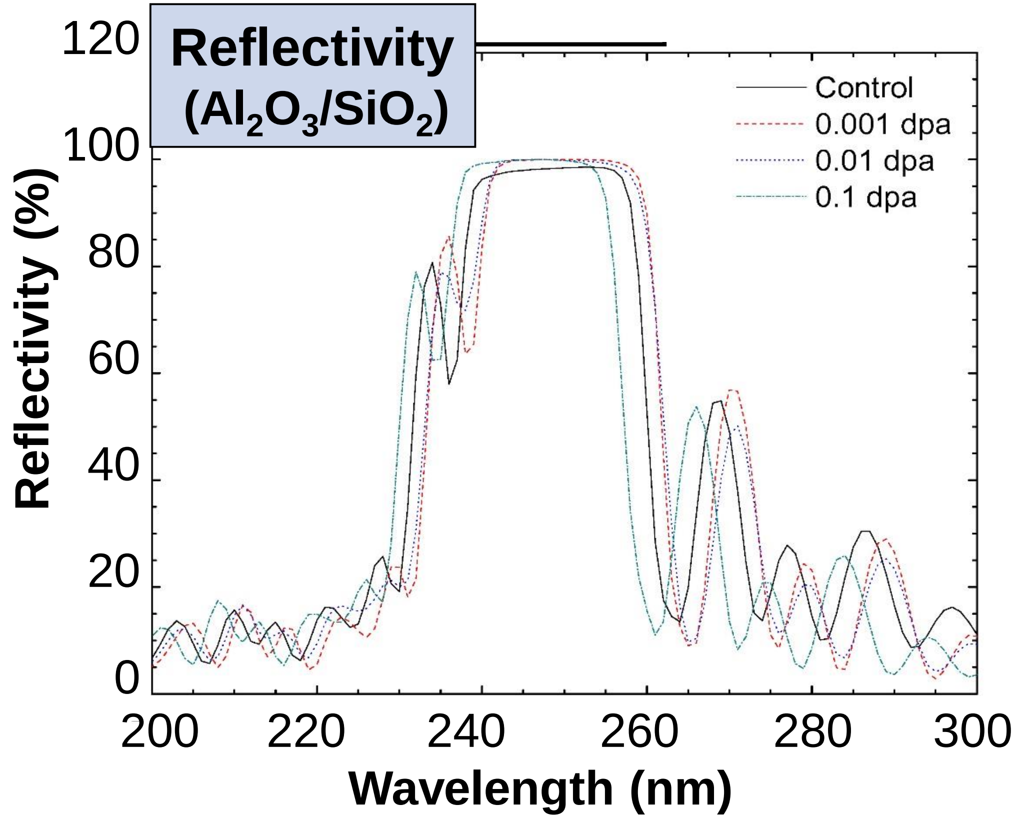
Mark Tillack (UCSD)

First dielectric mirror predicted to be subject to 0.02 dpa. New dielectric design exceeds this by at least 5 x.

The "key":
- **Match neutron-induced swelling in substrate and mirror layers**

Experiment:
- **Expose in HIFR (ORNL Reactor)**
- **Prototypical fluence, temperature**

Measurements:
- **Reflectivity**
- **Laser damage threshold**

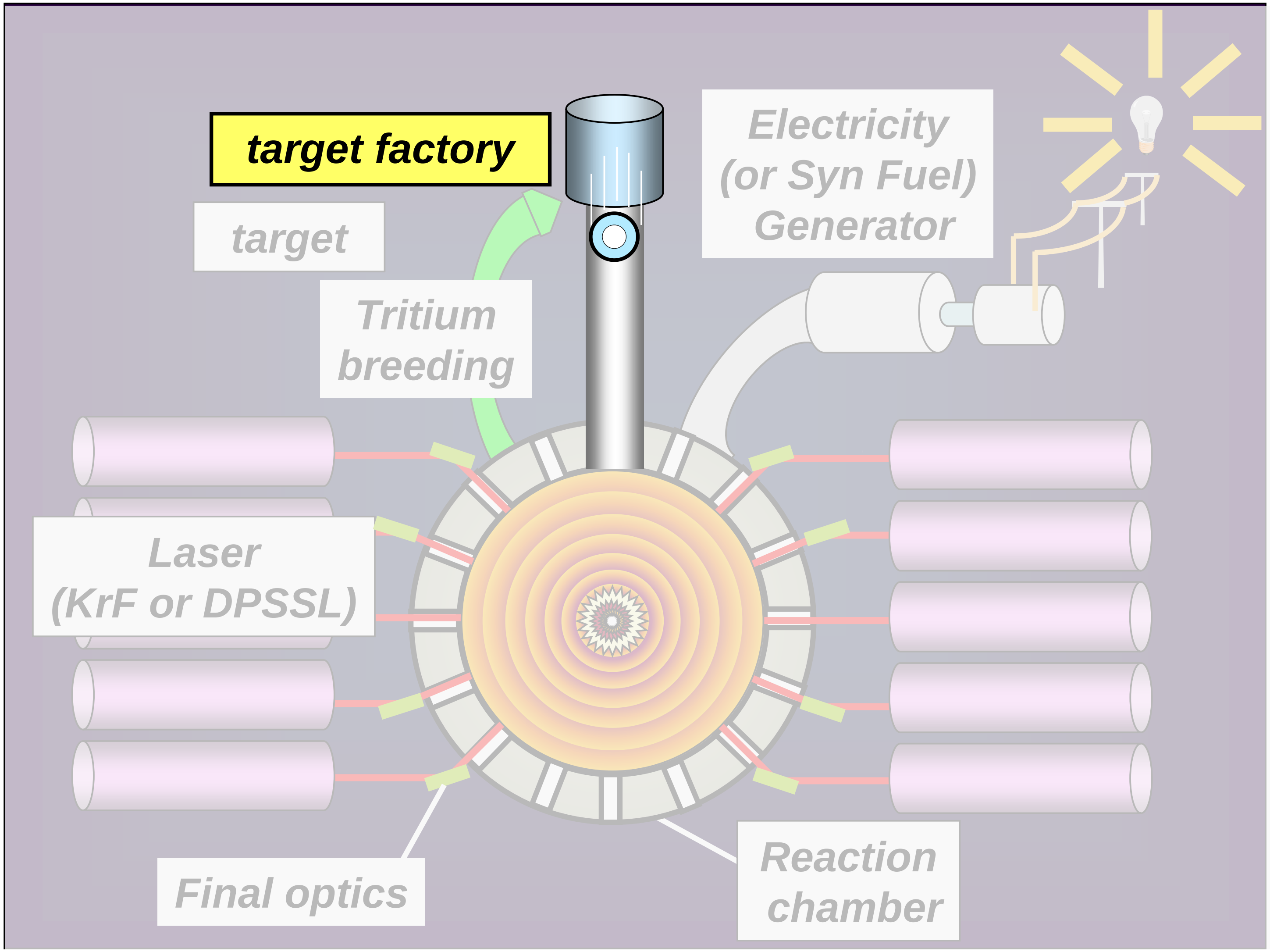


Laser Damage Threshold (as determined by reflectivity (Al_2O_3/SiO_2)

No dpa	0.001 dpa	0.01dpa	0.1 dpa
86-87%	84-86%	78-83%	83-84%

Lance Snead (ORNL)
Tom Lehecka (Penn State)
Mohamed Sawan (Wisconsin)

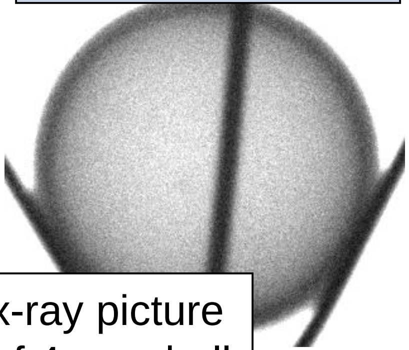
TARGET FABRICATION



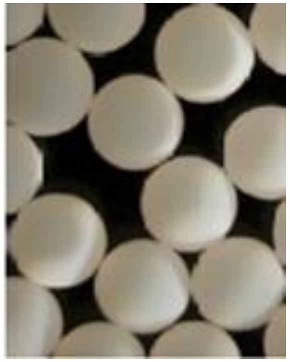
Target fabrication:

- Mass produce foam shells that meet specs
- Fluidized bed for mass cryo layering
- Estimate Cost < $0.17 each

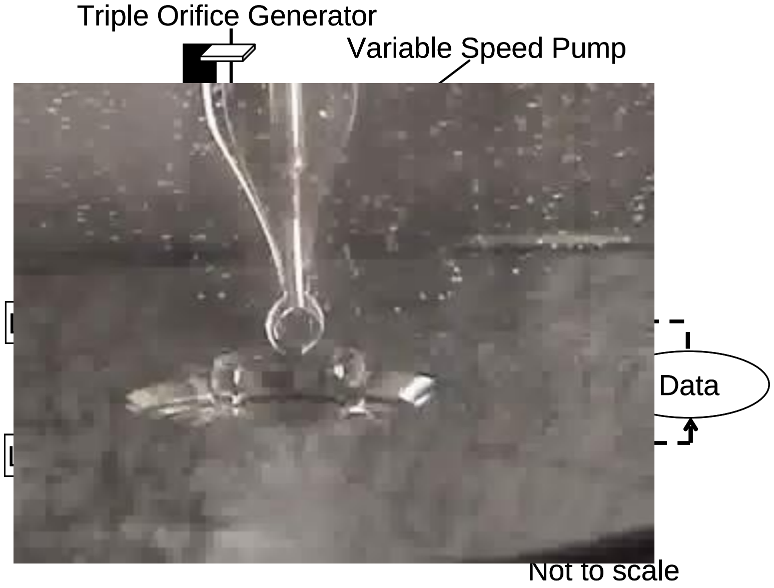
Foam shells (100 mg/cc)



x-ray picture of 4mm shell



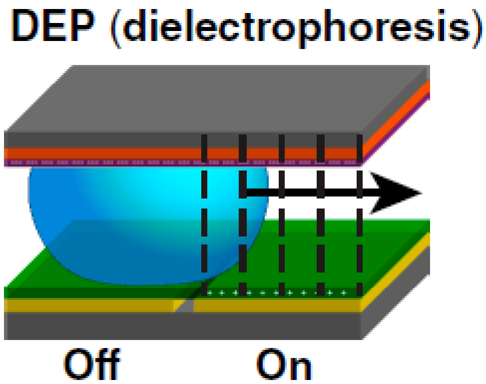
Mass Production: 22 shells/min



Cryogenic Fluidized bed to make smooth DT ice

GA, Schaffer, UCSD

"Micro-Fluidic Electro mechanical" approach pursued by University of Rochester, LLE may be able to make complete targets in one process

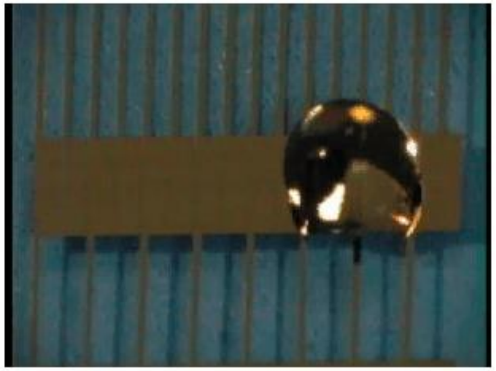


Principle:

Programmable electric fields are used to form precise droplets and move fluids

Demonstration:

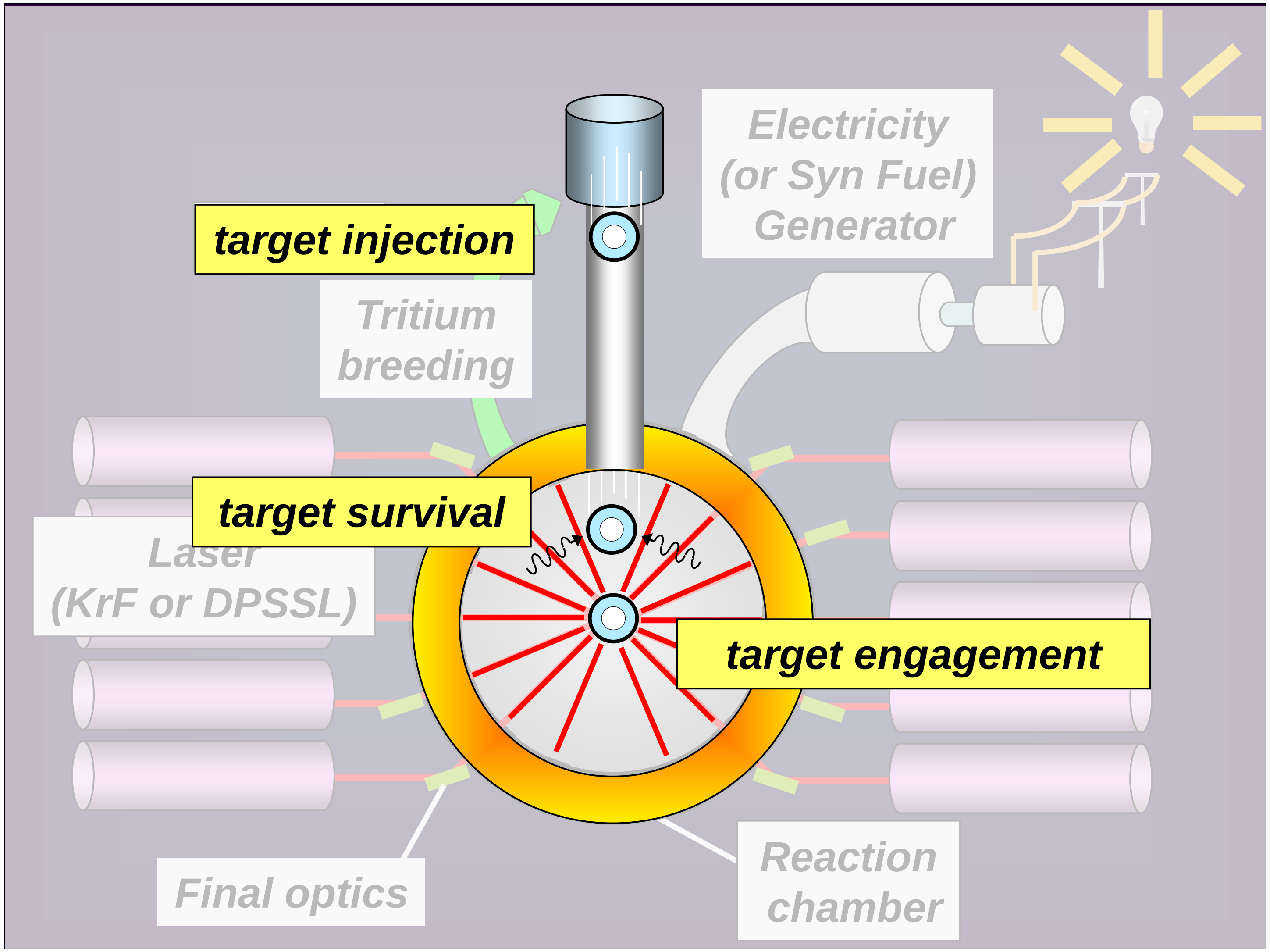
Foam shells of correct dimensions. Made by combining and manipulating precisely formed water and oil droplets



D. Harding, LLE

UR LLE

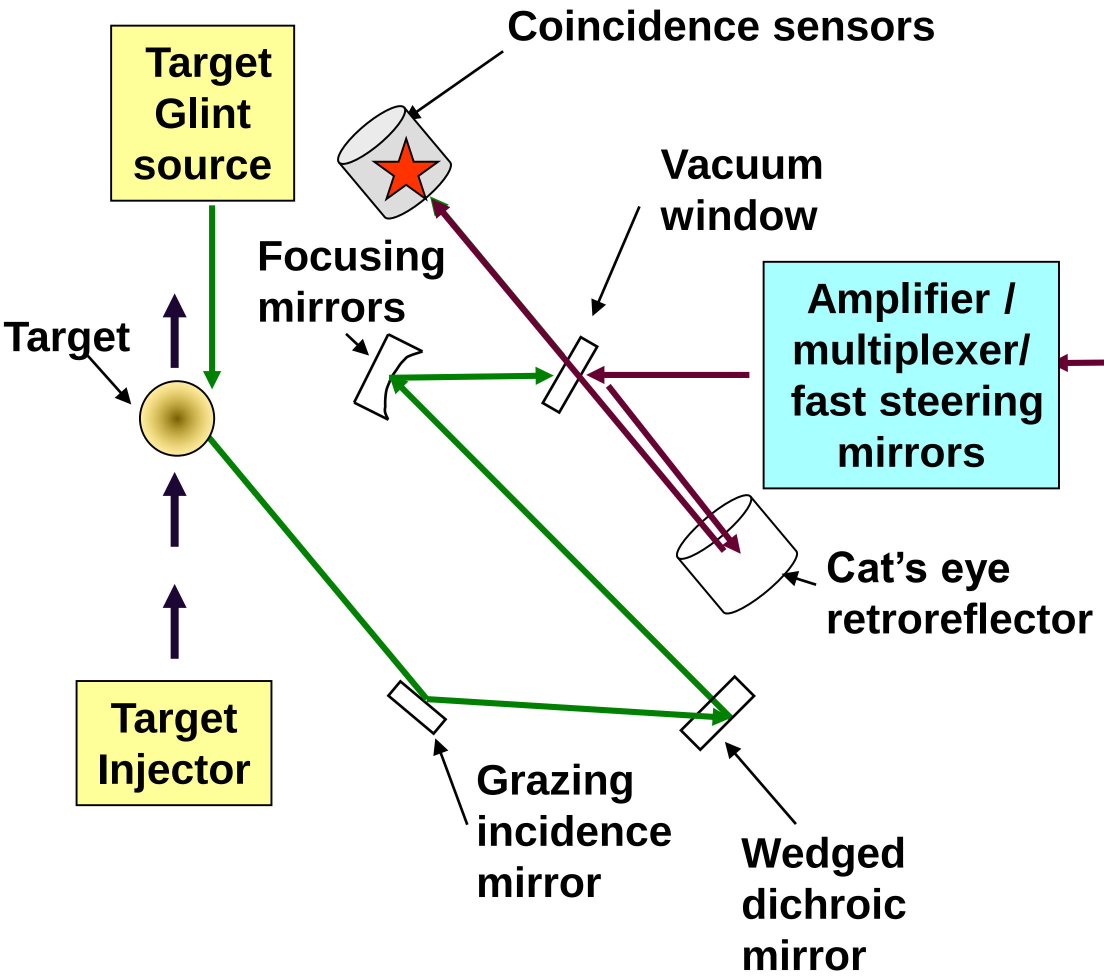
TARGET:
INJECTION, SURVIVAL, and ENGAGEMENT

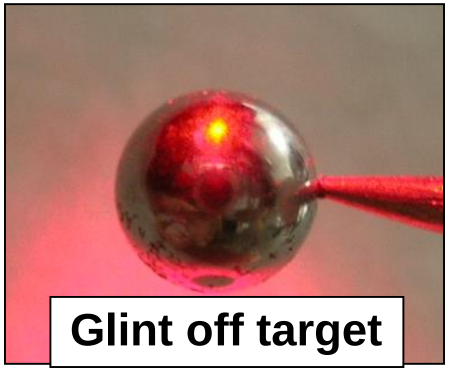


Light Gas Gun Prototype Injector

- Demonstrated 5 Hz operation
- Achieved required 400 m/sec
- Demonstrated separable sabot (and recovery)
- Target placement accuracy +/-10 mm

Target Engagement:
Concept based on detecting "Glint" off the target.

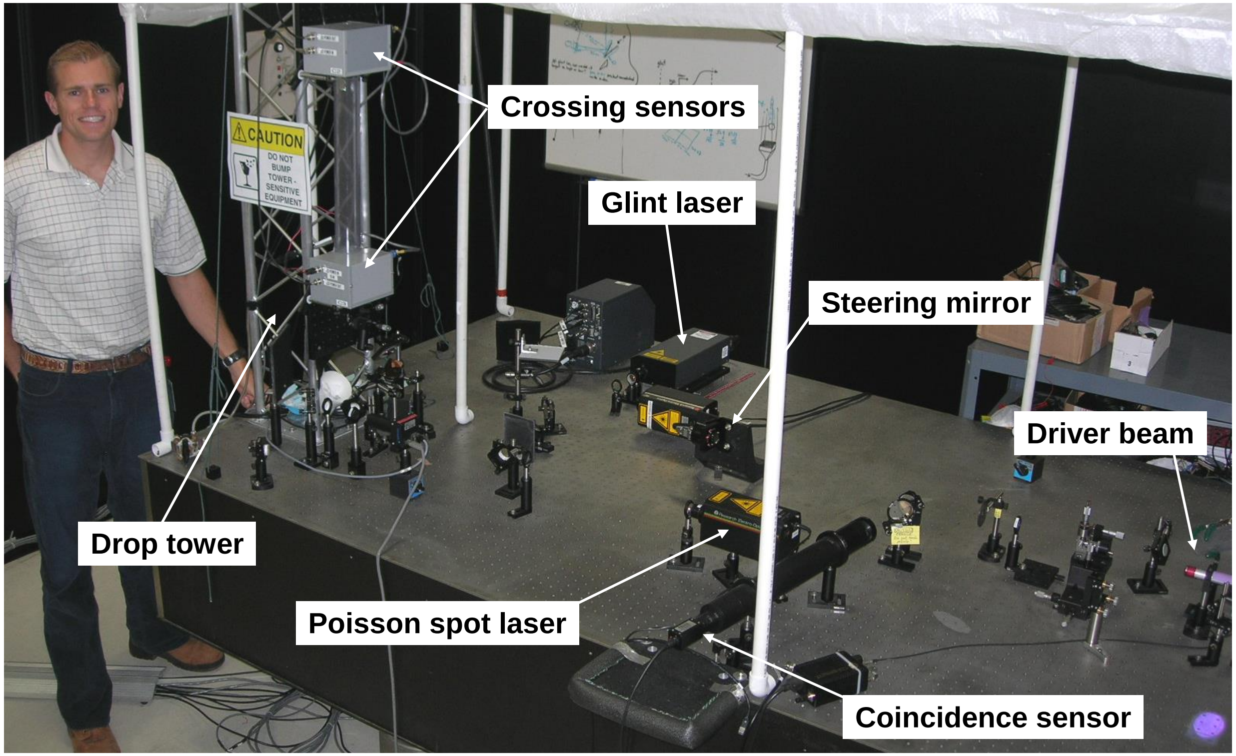


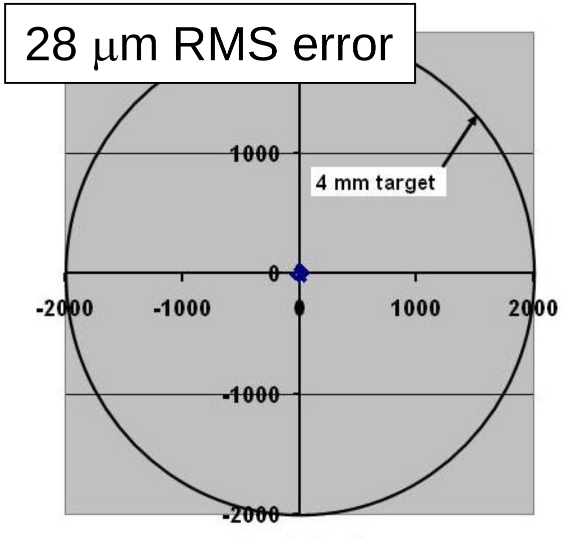


Glint off target

Lane Carlson (UCSD)
General Atomics

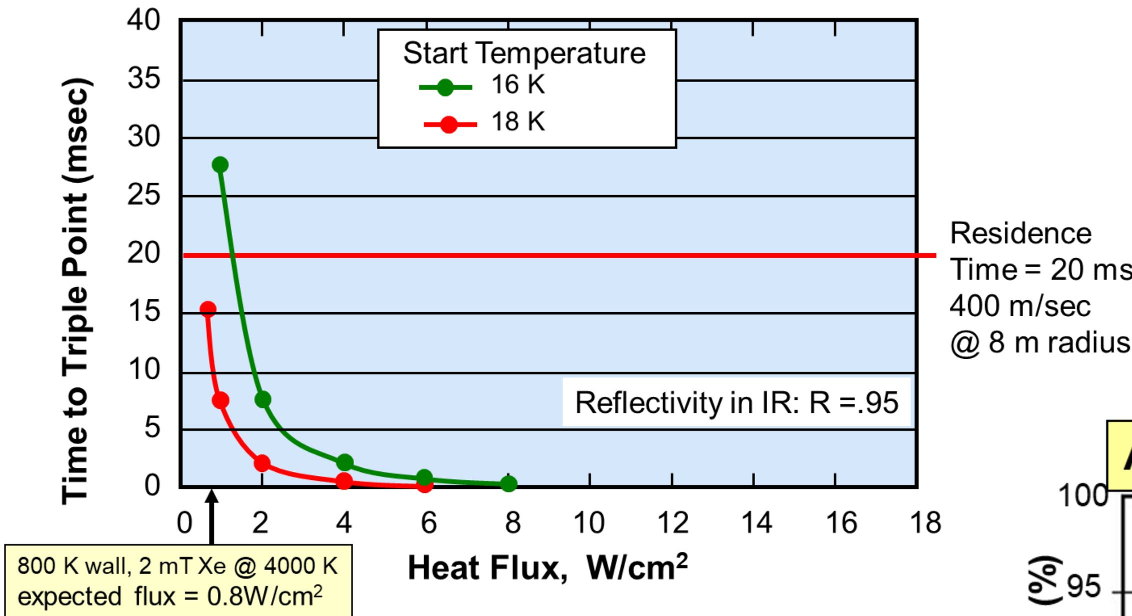
Target Engagement: Bench test: Mirror steers laser beam to target within 28 um. Need ~20





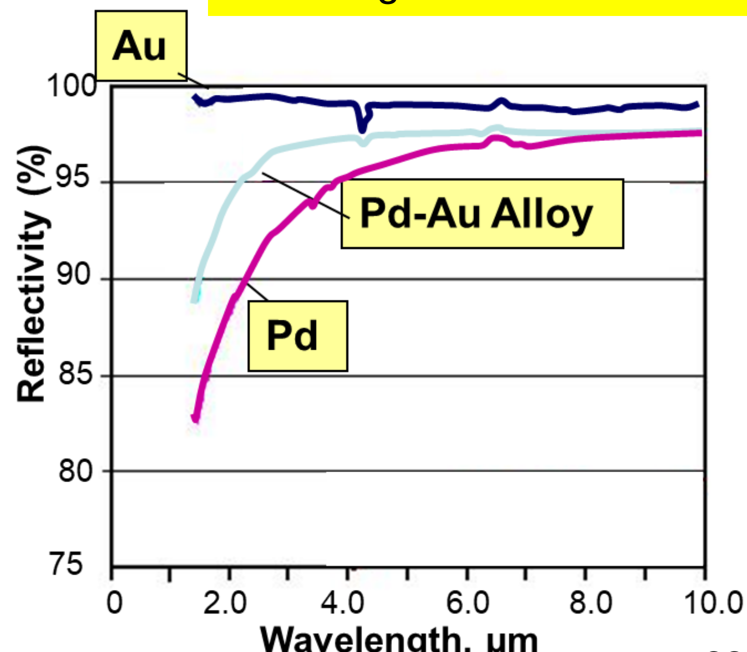
Lane Carlson (UCSD)
General Atomics

Calculations shows Pd-Au alloy coated Direct Drive Targets can "survive" injection into the chamber

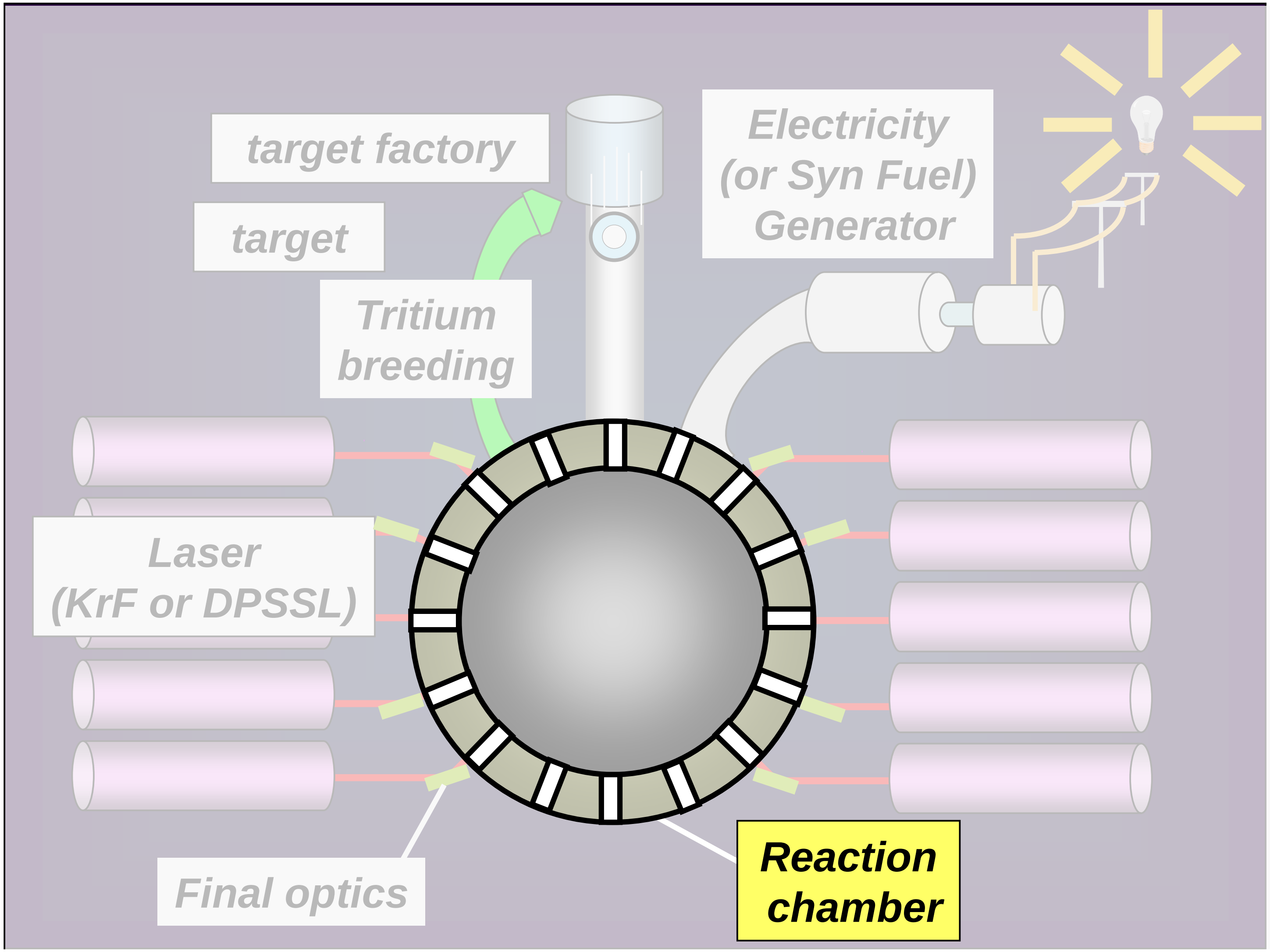


A Raffray (UCSD)

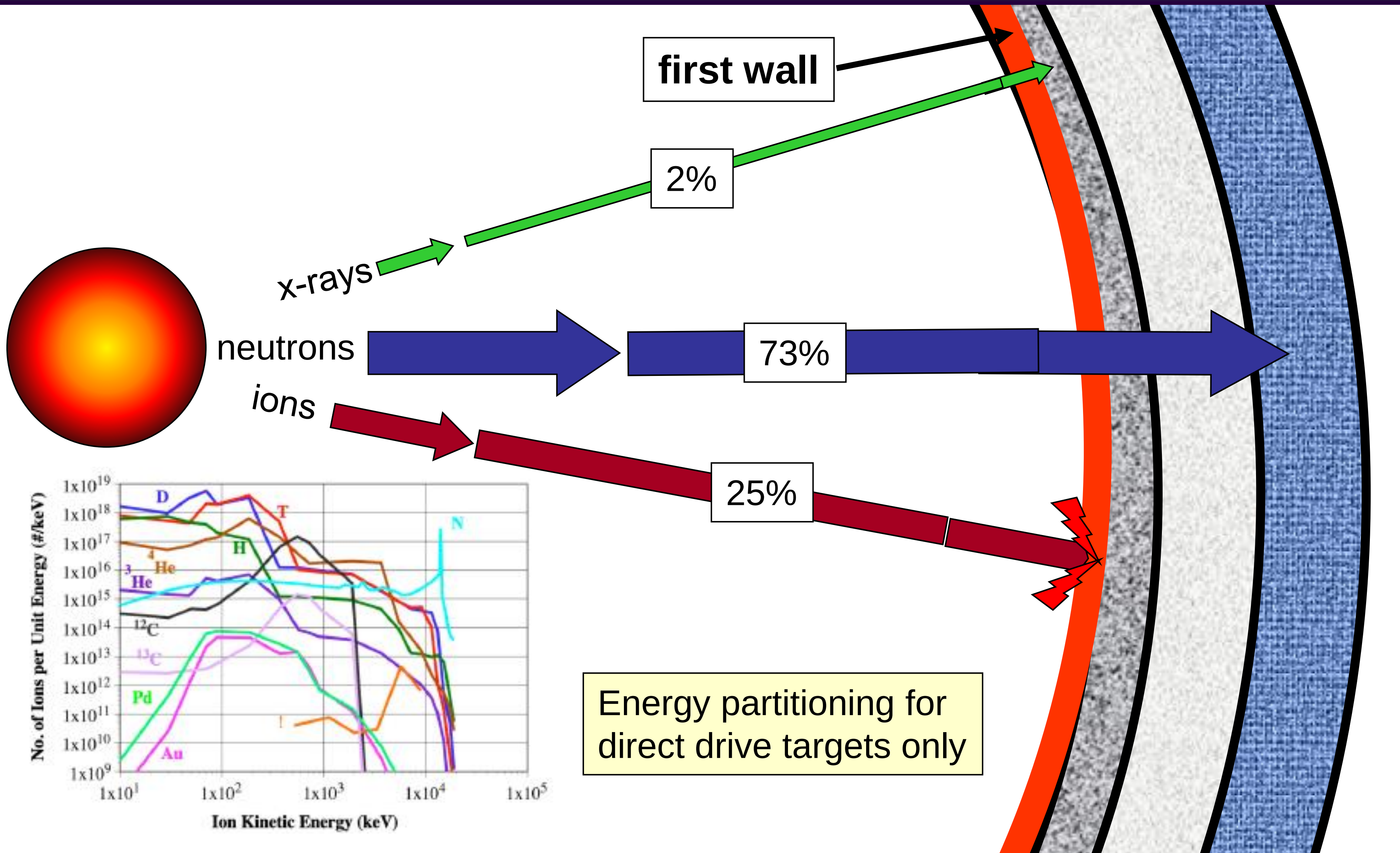
Pd-Au alloy provides good IR reflectivity & allows pressure fill of target.



REACTION CHAMBER



The "first wall" of the reaction chamber must withstand the steady pulses of x-rays, ions and neutrons from the target.



Energy partitioning for direct drive targets only

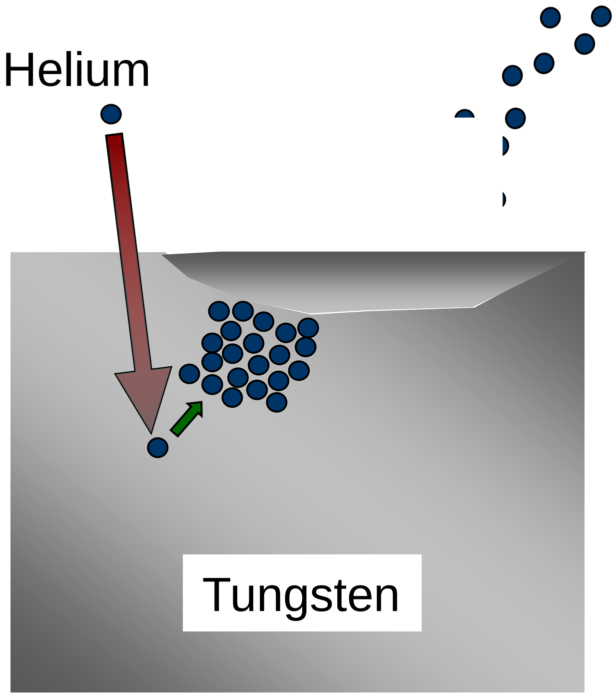
The problem of helium retention may be solved with "nano-engineered" armor

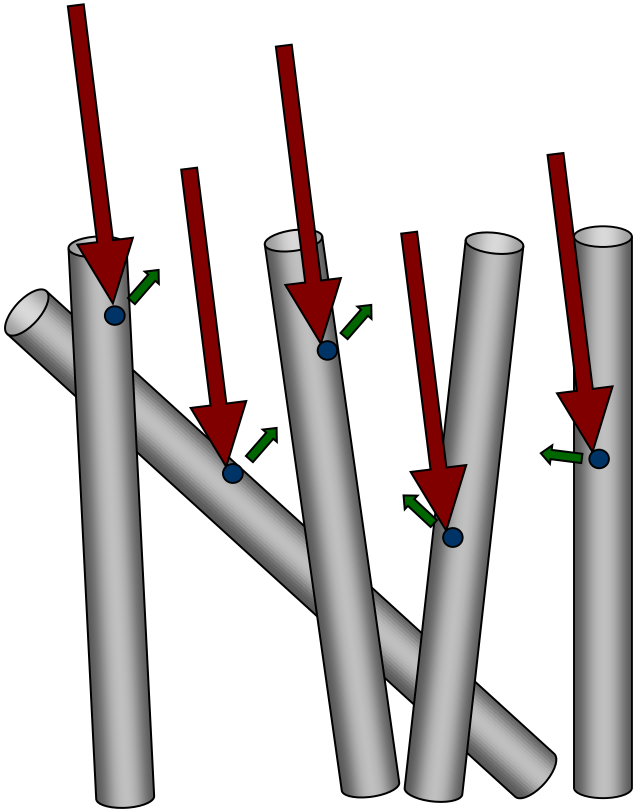
The Problem:

- He ions penetrate deeply (1-5 μm)
- Have short migration length (150 nm)
- Agglomerate into bubbles
- Exfoliate the wall

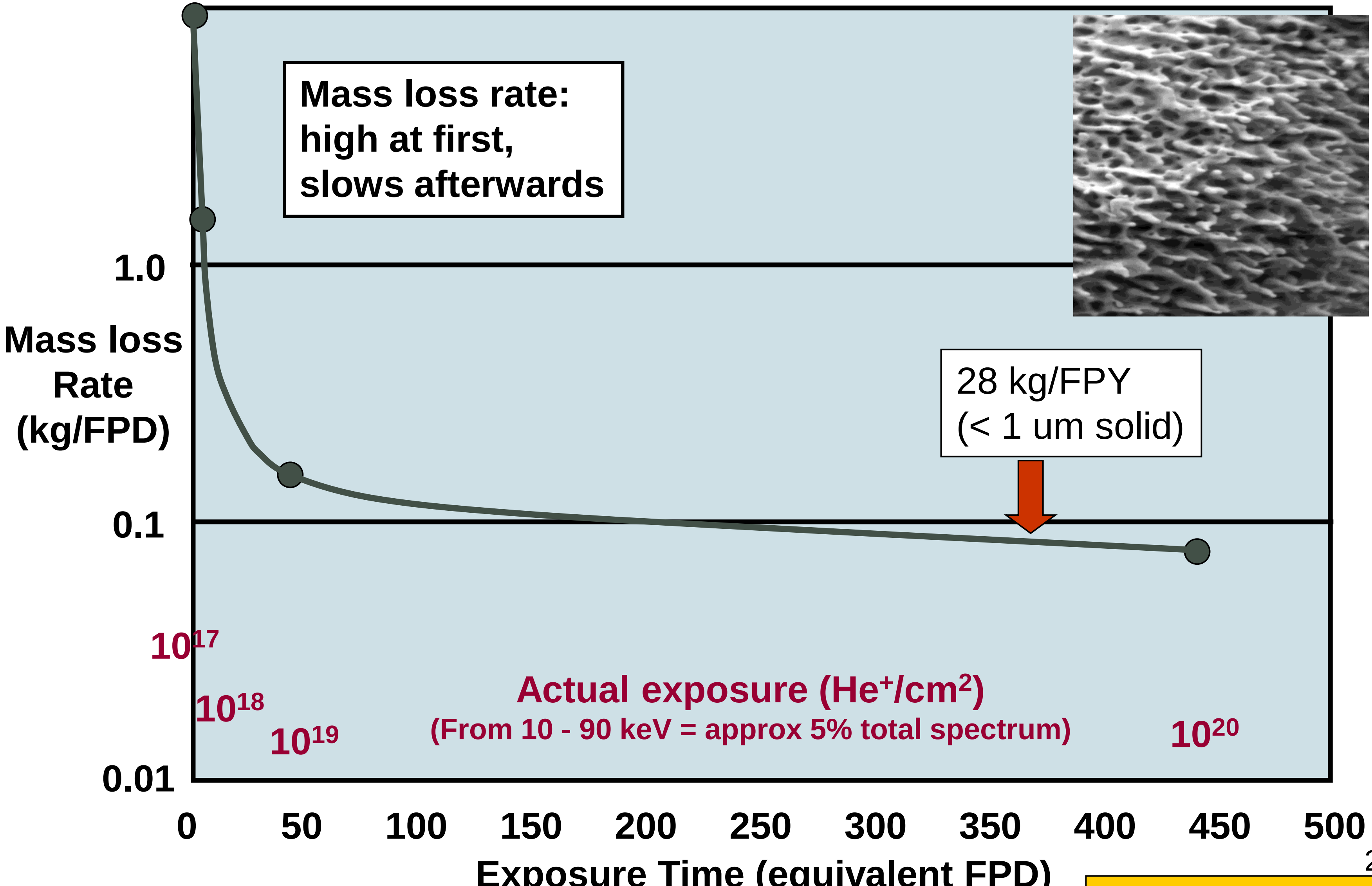
The Solution:

- Make armor from tungsten fibers
- Diameter < 150 nm
- Helium stops close to free surface
- He migrates out (cyclic heat helps!)





First "Nano-Engineered" Tungsten helium retention experiments are encouraging

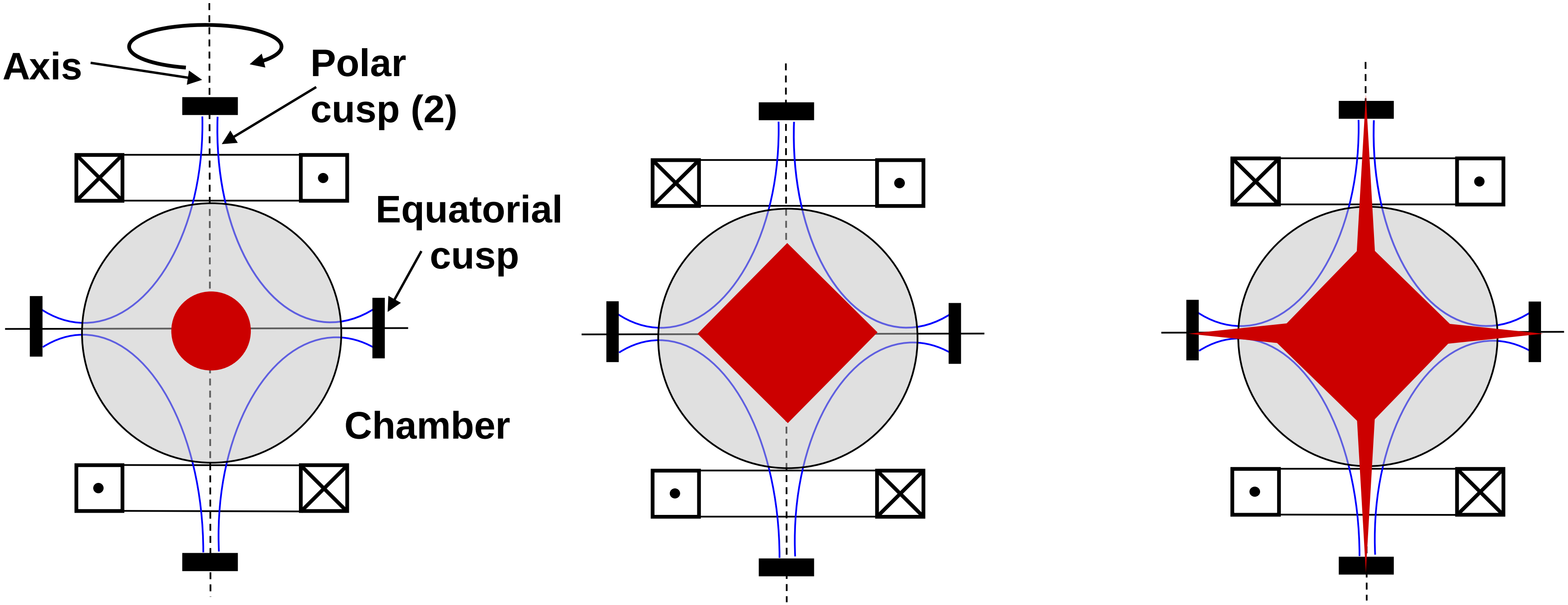


Sam Zenobia (Wisconsin)

Magnetic Intervention:

Cusp magnetic field keeps ions off the wall

(in Plasma Physics terms: Conservation of $P_\theta = mrv_\theta + (q/c)\, rA_\theta = 0$



- **Plasma starts at center (A_θ = 0,v_θ=0)**
- **Expansion initially spherical**

- **Ions expand into increasing field.**
- **Expansion stops when $mrv_\theta = (q/c)rA_\theta$**

- **Ions, *at reduced power*, leak into external dumps**

m = mass
q = charge

v_θ = azimuthal velocity
A_θ = azimuthal vector potential

HAPL summary

The HAPL program identified and advanced many of the essential S&T challenges to laser IFE – by far the broadest laser IFE effort to date. Funding peaked @ $25M/year

HAPL is documented in a large number of publications and the presentations at the 19 meetings are available at:

http://qedfusion.org/HAPL/MEETINGS/0804-HAPL/program.html

The ARPA-E & FES support the BETHE* IFE Effort

* Breakthroughs Enabling THermonuclear-fusion Energy

- The BETHE IFE program seeks to advance approaches that can reduce the cost of fusion power plants and the electricity that they generate.
- LLE is developing broad bandwidth UV laser sold state laser technology (351 nm) while NRL is developing broad bandwidth ArF laser technology at deeper UV (193 nm)
- By suppressing LPI both technologies will enhance design space for laser fusion implosions.
- ArF's 193 nm light increases the hydrodynamic efficiency of direct drive implosions. Simulations indicate it could enable the gain needed for IFE with less than 1 MJ laser energy.
- Research at NRL so far indicates there is no fundamental obstacle to building MJ class ArF laser systems for IFE.

Electra is now an ArF laser test bed

The deep UV and multi-THz light could provide a path to smaller lower cost laser fusion power.

https://www.nrl.navy.mil/Media/News/Article/2819749/nrl-argon-fluoride-laser-to-advance-fusion-energy/

The Vision…A plentiful, safe, clean energy source

A 100 ton (4200 Cu ft) ***COAL*** hopper runs a 1 GWe Power Plant for ***10 min***

Same hopper filled with ***IFE targets***: runs a 1 GWe Power Plant for ***7 years***